

NASA Supersonics Research — Leading Toward Quiet Supersonic Flight!!



Presentation at
EAA AirVenture
July 2022



Don Durston
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Commercial Supersonic Technology Project

Outline



- Brief history of supersonic flight
- Shock waves and sonic booms
- Sonic boom pressure signatures and loudness
- Tools for studying quiet supersonic flight
 - CFD (Computational Fluid Dynamics)
 - Wind tunnels
 - Flight test
- Quesst Mission
 - X-59 airplane
 - Mission profile
 - Flight simulations
 - Wind tunnel data validations
- Video: Supersonic flight research leading to Quesst

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Initial Supersonic Speed Records

1st airplane to exceed Mach 1:

Bell X-1, October 14, 1947, flown by
Chuck Yeager
— Mach 1.06 at 43,000 feet altitude



$$\text{Mach number} = \frac{\text{aircraft speed}}{\text{speed of sound}}$$

Speed of sound @ 43,000 ft = 662 mph

Mach 1.06 @ 43,000 ft = 702 mph

1st airplane to exceed Mach 2:

Douglas D-558-II Skyrocket, November 20, 1953, flown by
Scott Crossfield — Mach 2.005 at 62,000 feet altitude



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1st airplane to exceed Mach 3:

Bell X-2, September 27, 1956, flown by Milburn Apt
— Mach 3.196 at 65,500 feet altitude



Operation Bongo II



- Starting in February 1964, the FAA and U.S. Air Force conducted a study of the effects of sonic booms on the public and on urban structures
- For 6 months, F-101 Voodoos, F-104 Starfighters, F-106 Delta Darts, and B-58 Hustlers flew eight supersonic flights per day over Oklahoma City
- Boom intensities of 1 to 2 psf at ground level were created
- Almost 10,000 complaints of building damage were filed—mostly shattered windows and broken plaster—and there were thousands of personal complaints from individuals
- Negative publicity about the tests led to the the 1971 cancellation of the Boeing 2707 project and to the United States' complete withdrawal from SST design



Commercial Supersonic Transports

*** *Supersonic over water only* ***

Concorde

- 20 aircraft built, 14 used for commercial service by British Airways and Air France
- 1st flight: 3/2/69
- Cruised at Mach 2 and > 50,000 feet altitude
- Passenger service from 1969 to 2003



Tupolev Tu-144

- 16 aircraft built, 14 used for commercial service by Aeroflot
- 1st flight: 12/31/68
- Cruised at Mach 2 and 52,000 ft altitude
- Passenger service from 1975 to 1978



Concorde Take-Off and High-Altitude Sonic Boom



The Concorde was very loud on take-off *and* so was the boom from high altitude

*Video removed to reduce file size,
video available from author upon request*

[https://www.youtube.com/
watch?v=5MCETiKCLhc](https://www.youtube.com/watch?v=5MCETiKCLhc)

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Air Transport Speeds at Subsonic Limits

Aside from the Concorde, commercial air travel has been limited to less than 600 mph

Airplane	Year of introduction	Cruise Mach	Cruise Speed (mph)
Boeing 707	1958	0.82	540
Concorde	1976	2.0	1,320
Boeing 787	2009	0.85	560



Boeing 707



Concorde



Boeing 787

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Blue Angels High Speed Passes Video

Three solo passes over San Francisco Bay during Fleet Week



*Video removed to reduce file size,
video available from author upon request*

[https://www.youtube.com/
watch?v=K7rAUu8djZ4](https://www.youtube.com/watch?v=K7rAUu8djZ4)



Blue Angels High Speed Pass Video

One more solo pass over San Francisco Bay

Watch for condensation over various parts of the aircraft caused by local acceleration of the flow



*Video removed to reduce
file size, video available
from author upon request*

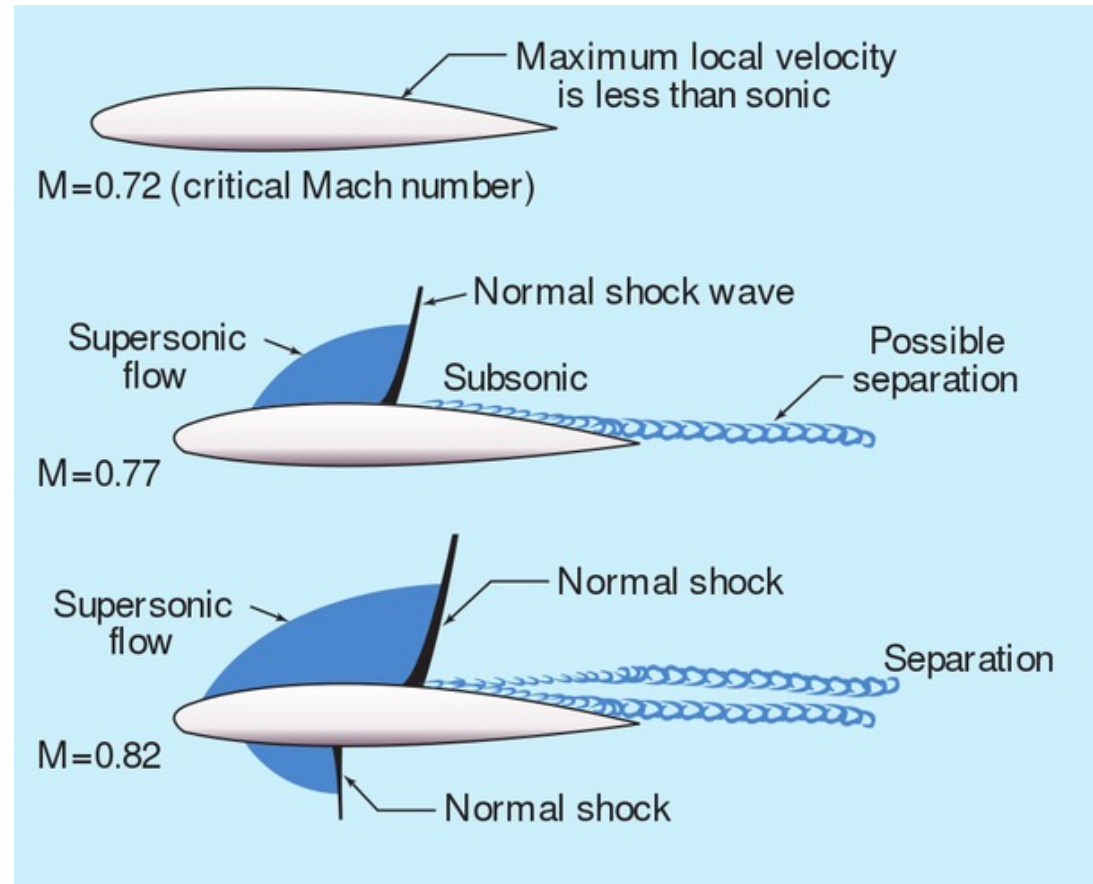
<https://www.youtube.com/watch?v=ONx0gSZ9NyM>

Blue Angel Shock Waves



Local Supersonic Flow

- Drag increases before reaching Mach 1
- Shock waves form and flow separation occurs
- This defines start of transonic speed regime





What is the Sound Barrier?

NOTHING!!!

- The uninformed media continually promotes the idea that there is a “barrier” that is “broken” when a jet goes supersonic, and that a sonic boom is produced at that moment (and only then) — this is not true!
- The aircraft produces shock waves continually while flying at supersonic speeds, and these are heard as a sonic boom
- The boom follows the airplane (just as waves from a boat are continuous), so everyone under or near the flight path of the airplane will hear the boom
- The only barrier to going supersonic is overcoming the high amount of drag



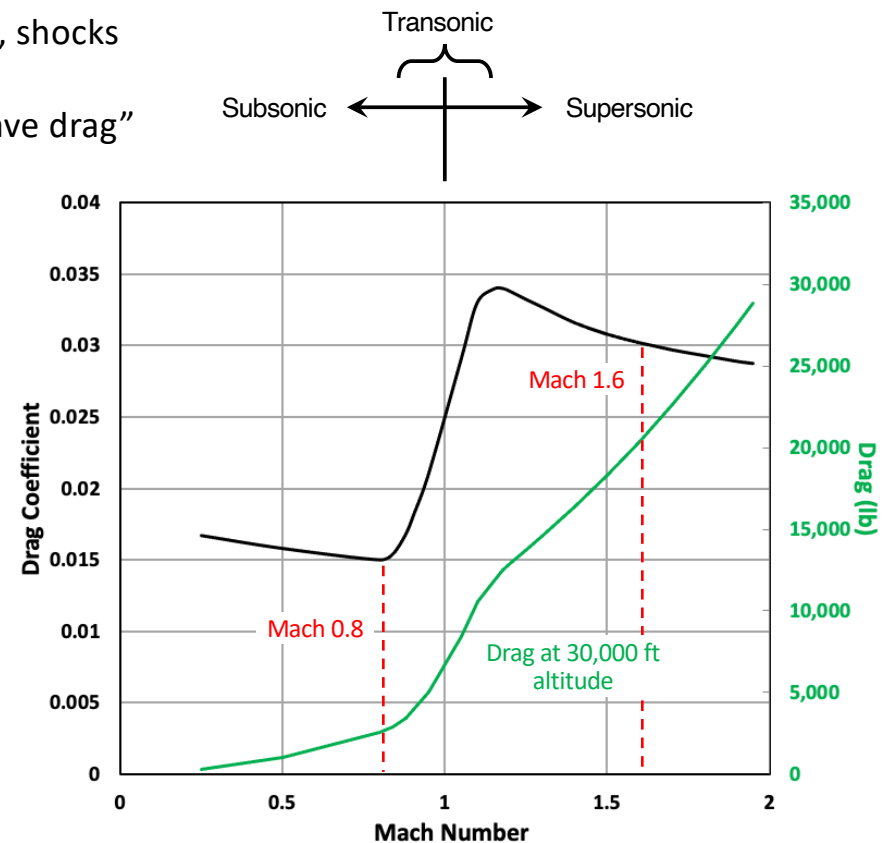
How High is the Drag?

- Aerodynamic drag increases dramatically from subsonic to supersonic speeds
- As incoming air is redirected around an aircraft at supersonic speeds, shocks are created
- The pressure of the air increases across these shocks and causes “wave drag”
- The more the air is redirected, the stronger the shock, and the greater the drag
- Drag *coefficient* increases through transonic speeds, but then lowers at higher supersonic speeds
- Actual drag *force* increases dramatically at high supersonic speeds, but is reduced as altitude is increased

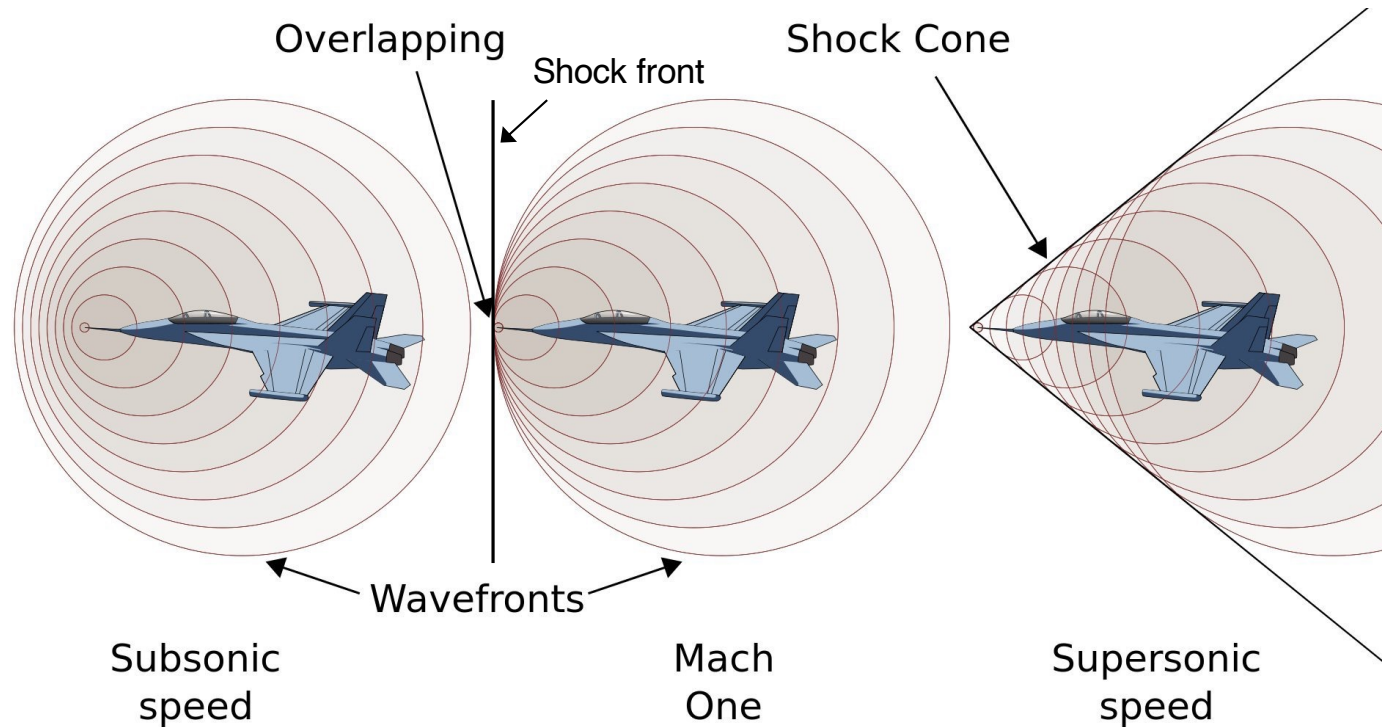
Example: Fighter airplane drag

Wing area (S): 600 sq ft

Mach	Altitude (ft)	Dynamic Pressure (q; psf)	Speed (mph)	$C_D = D/qS$ Drag Coefficient	Drag (lb)
0.8	30,000	282	542	0.015	2,530
1.6	30,000	1,126	1,084	0.030	20,400
1.6	60,000	270	1,059	0.030	4,900



What Makes a Sonic Boom?

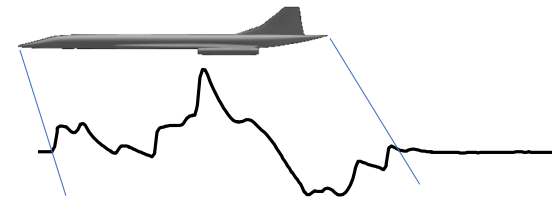


- Conical shock wave produces sonic boom at ground which moves with the airplane
- Boom is created over *entire* length of supersonic flight, just as a boat wake is continuous

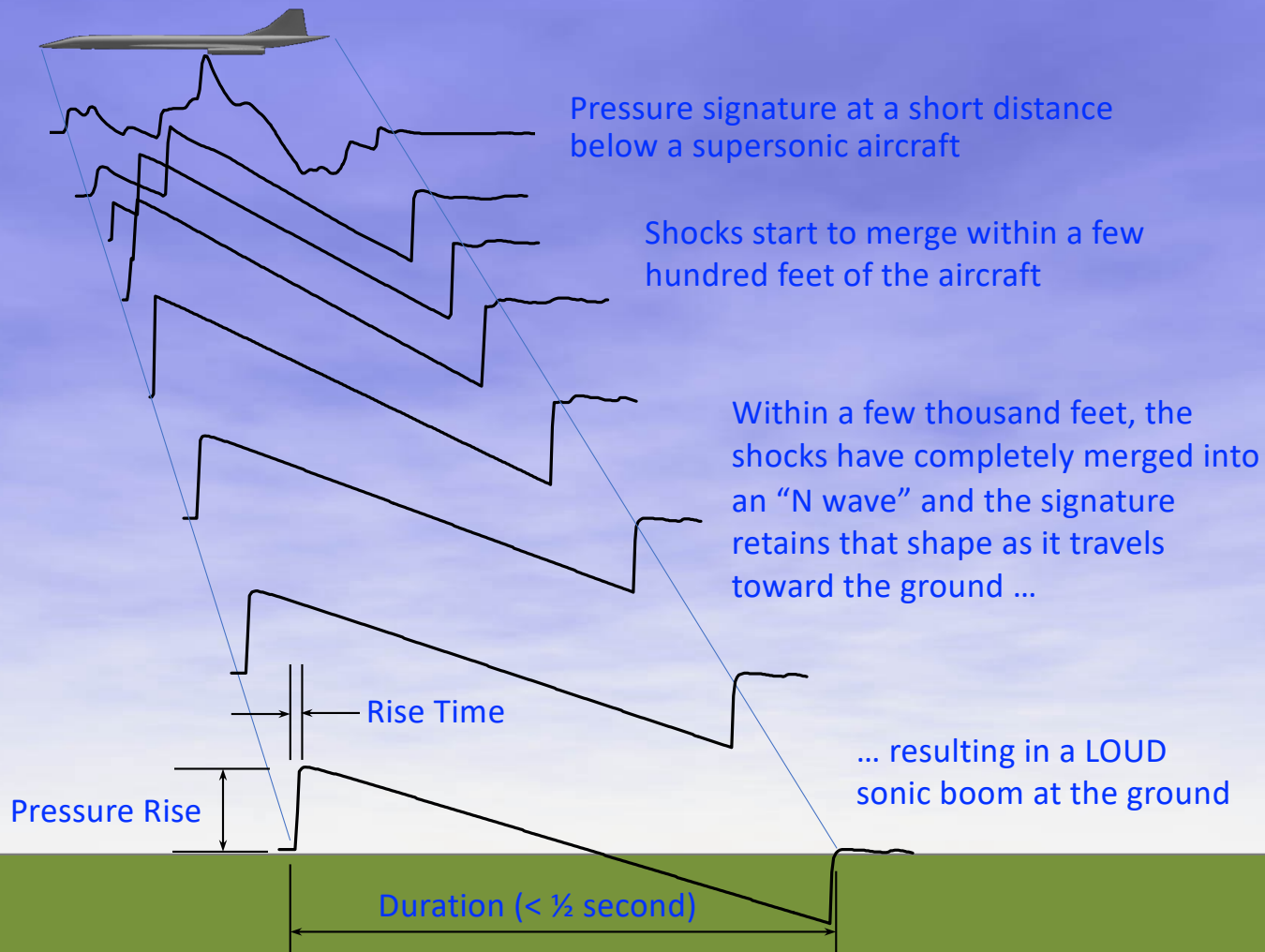
Outline



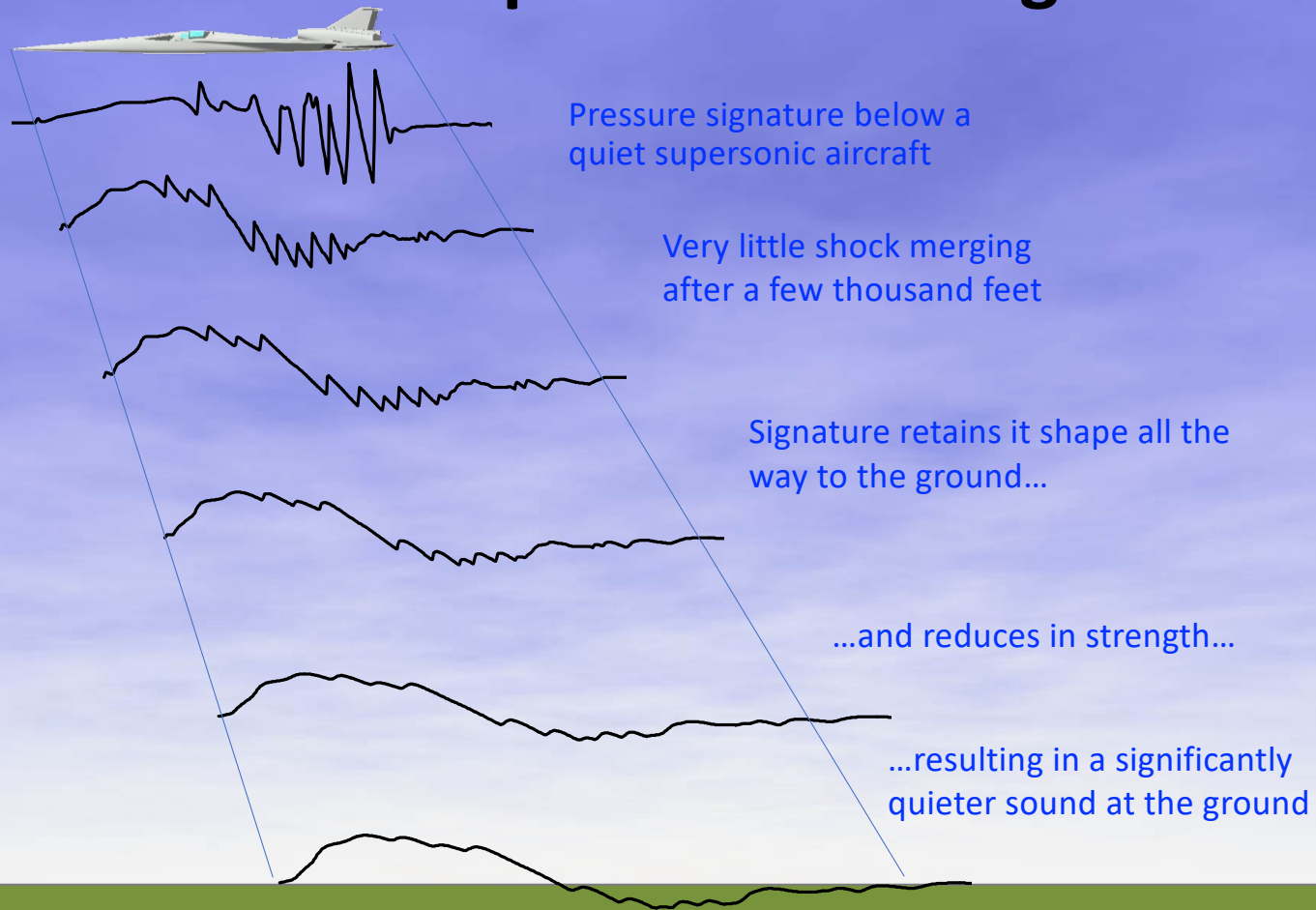
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Sonic Boom Basics: N-Wave Sonic Boom



Sonic Boom Basics: Shaped Pressure Signal



From Boom to Thump: How NASA is Addressing the Quiet Supersonic Design Technical Challenge



Objective

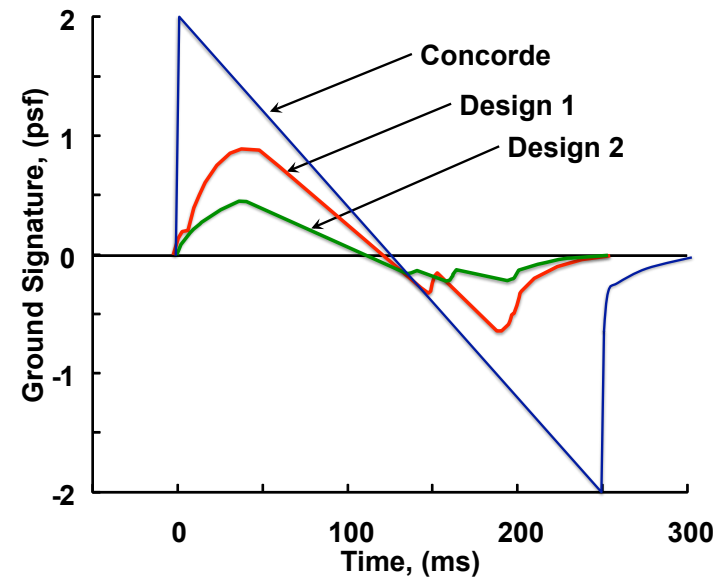
- Develop and validate tools and design approaches to enable the development of supersonic airliners with very little perceived supersonic noise:
<75 PLdB, or about 30 dB less than Concorde and typical military aircraft

Approach

- Build on 40+ years of sonic boom minimization research
- Improve usability, accuracy and speed of high-fidelity analysis tools for inclusion in the design process
- Develop new near-field & ground signature design targets that produce less noise, and allow more flexibility in the design process
- Conduct validation studies in wind tunnels and in flight

Result

- NASA's breakthrough technology development has been validated in wind tunnels, now ready for flight demonstration

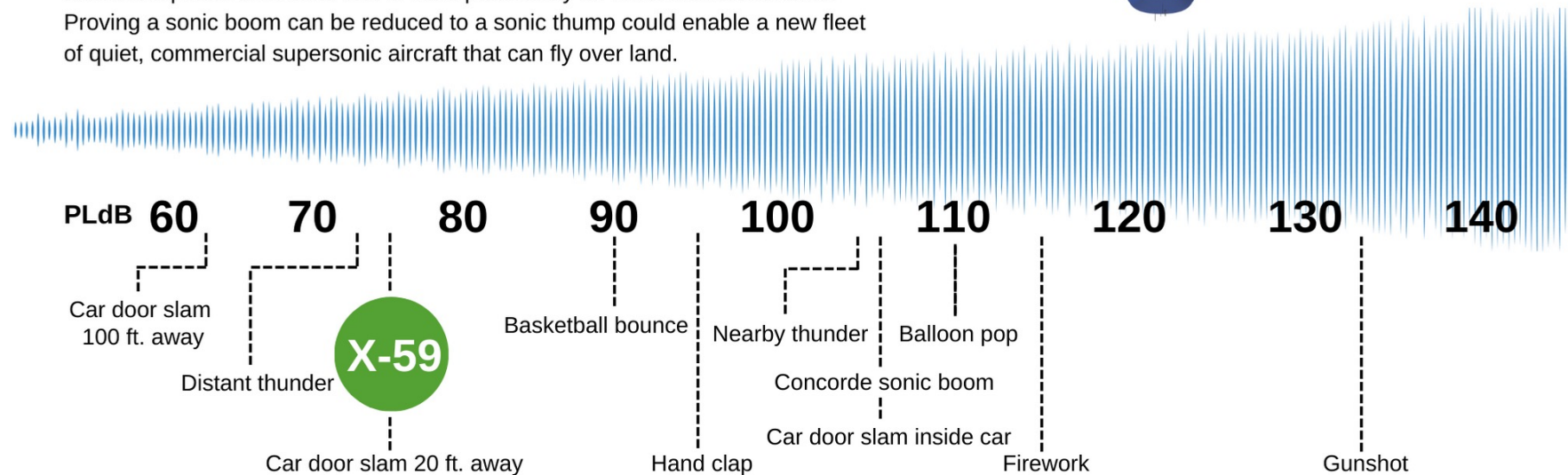


Sound Levels from Impulsive Noise Sources



Just how quiet will NASA's X-59 be?

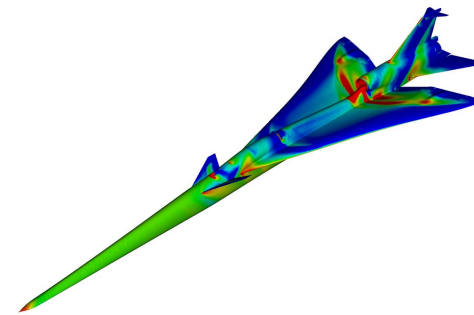
NASA's single-seat X-59 experimental aircraft will produce a barely audible sonic thump to people on the ground when cruising at supersonic speeds. In technical terms, the X-59's sonic thump will be around 75 Perceived Level decibels (PLdB) or less. PLdB is one of numerous scales, in decibels, that is used to understand human response to sounds and is used particularly for short duration sounds. Proving a sonic boom can be reduced to a sonic thump could enable a new fleet of quiet, commercial supersonic aircraft that can fly over land.



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Tools for Studying Quiet Supersonic Flight

**Wind
Tunnel
Test**

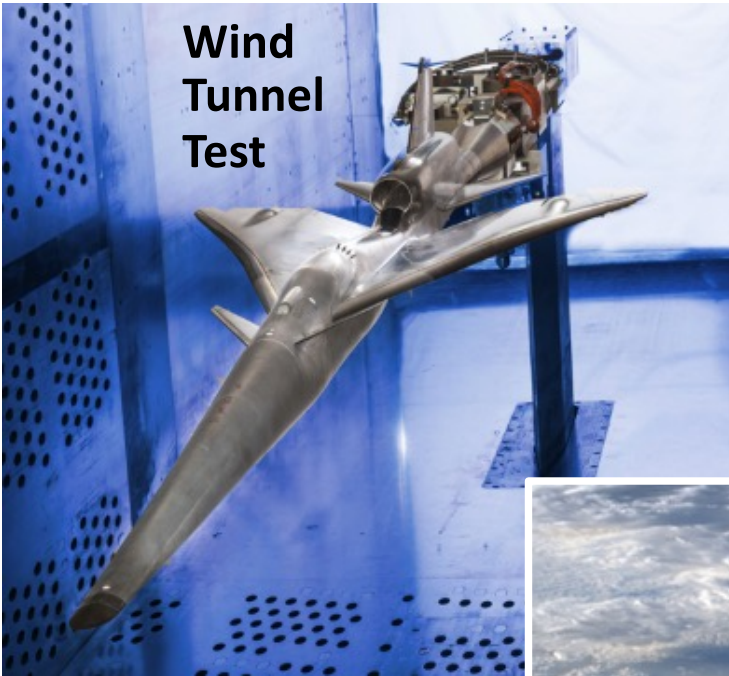


Image Credit: NASA Glenn Research Center

**Computer
Simulation**

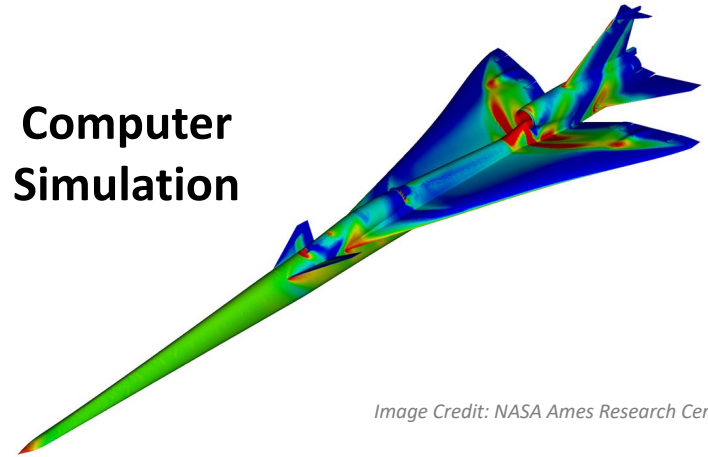


Image Credit: NASA Ames Research Center

Flight Test



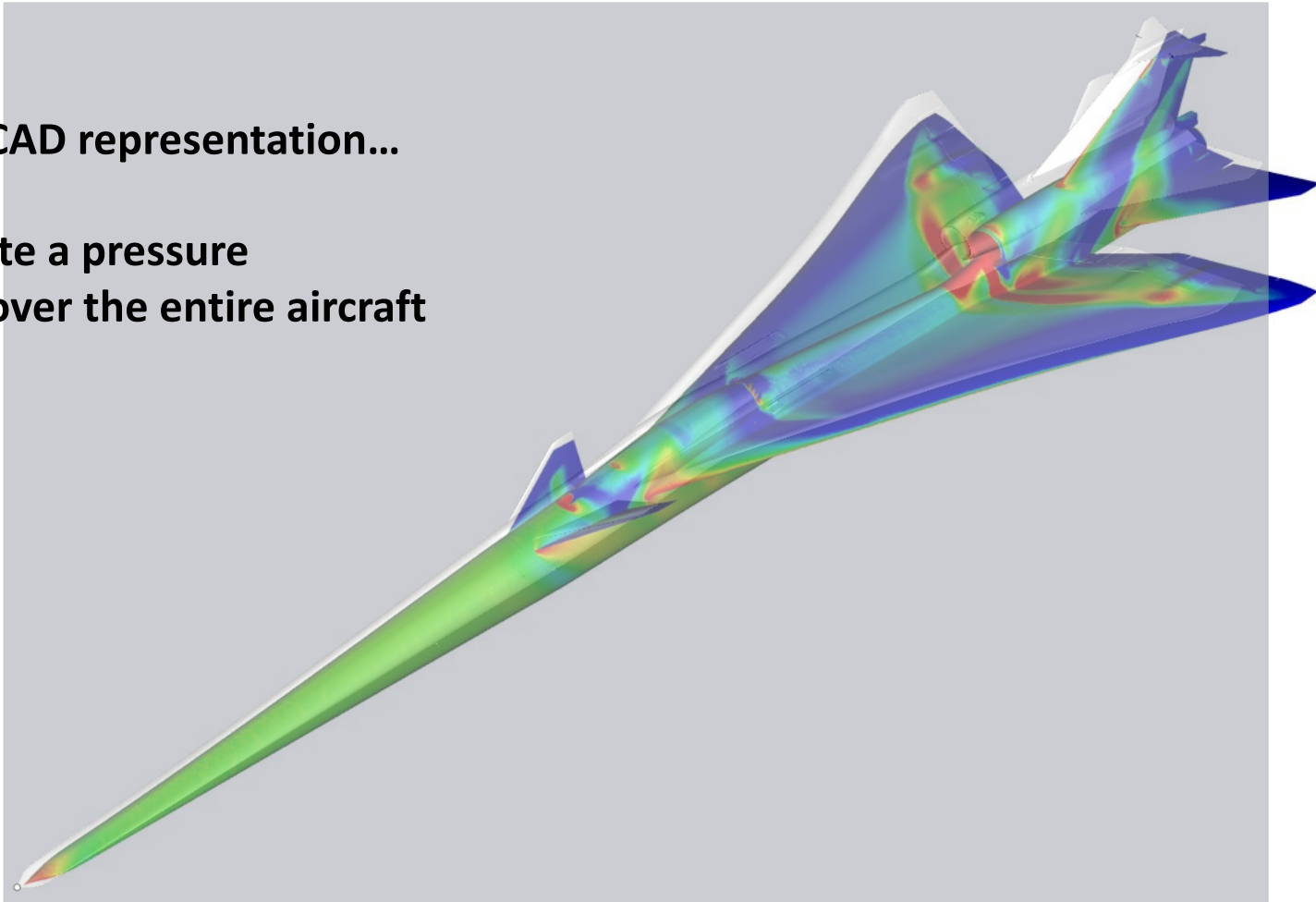
Image Credit: Lockheed Martin

Computational Fluid Dynamics (CFD) for Computer Simulation of Aerodynamics and Sonic Boom



Start with a CAD representation...

...and compute a pressure distribution over the entire aircraft



Shock Wave Predictions for X-59

Predictions of surface and flow field pressures by LAVA

- Shock waves (higher pressures) in red
- Expansion waves (lower pressures) in blue

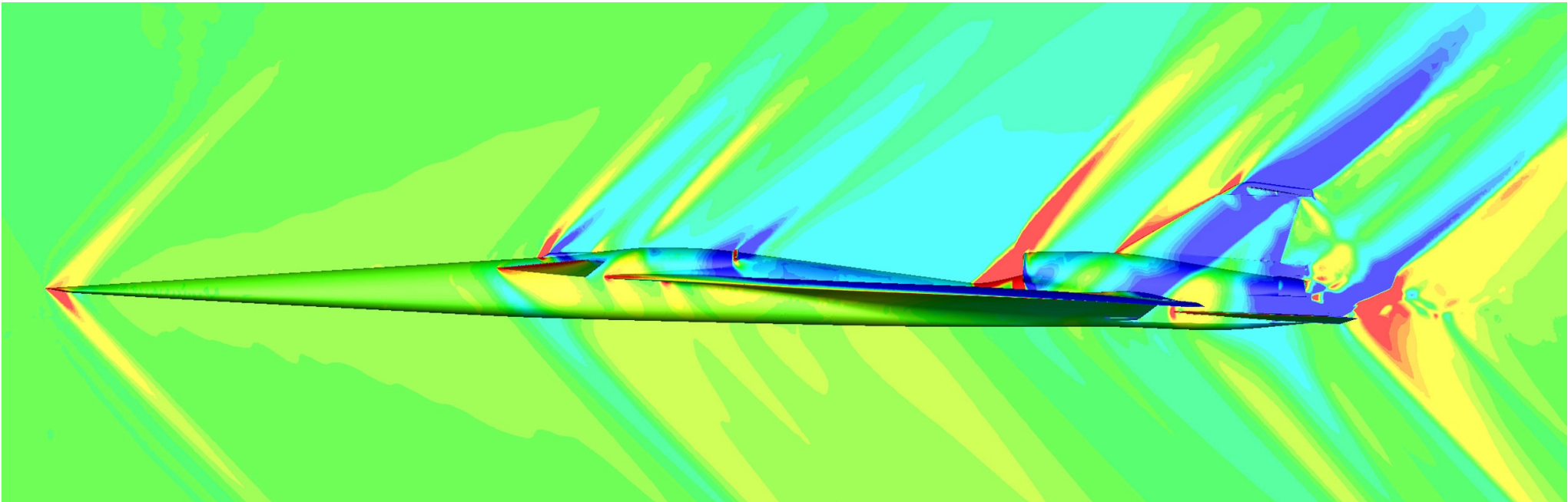
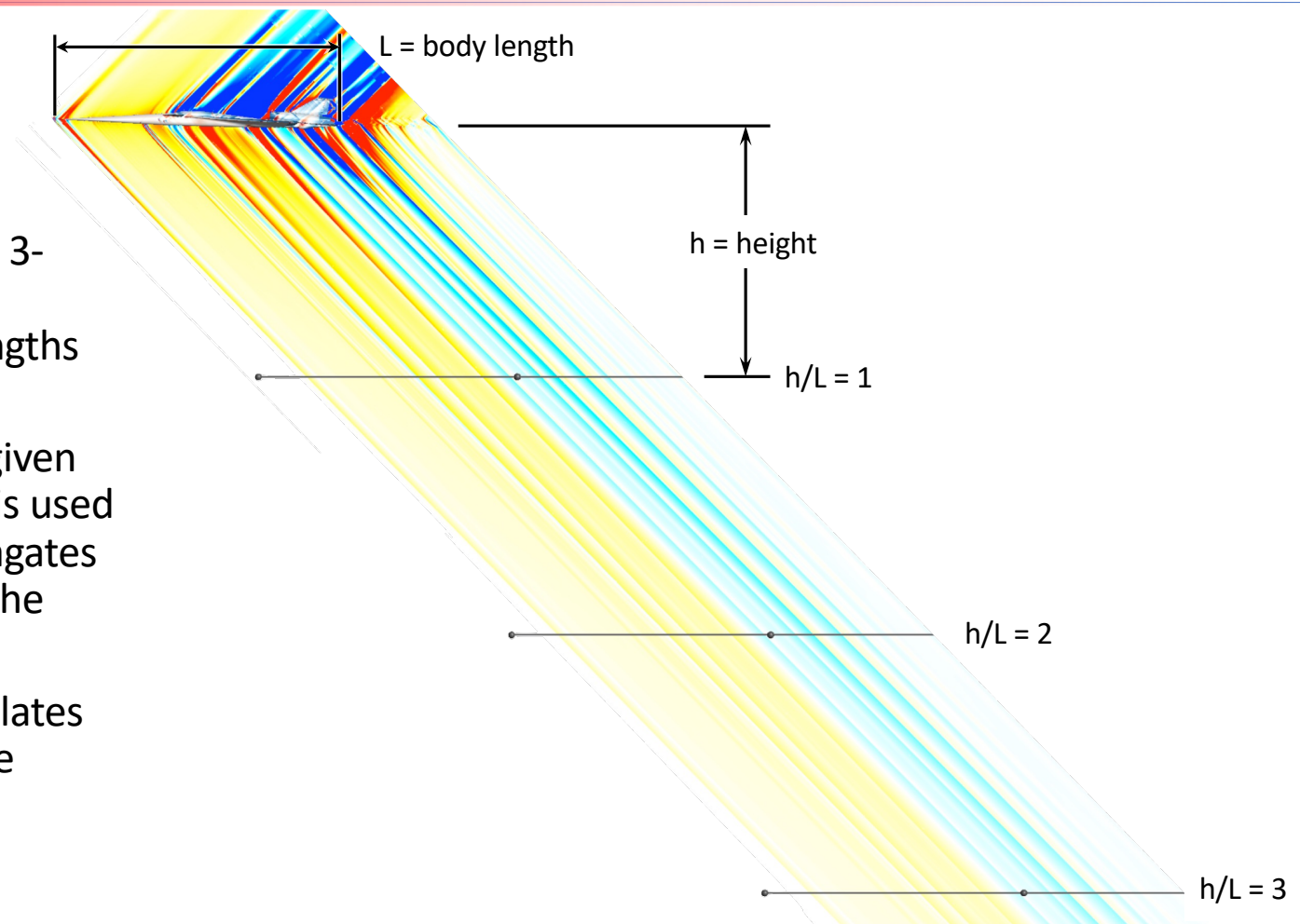


Image Credit: NASA Ames Research Center
<https://www.nasa.gov/specials/X59/tools.html>

Propagation of Shock Waves Towards Ground

- The Cart3D (Cartesian mesh, 3-dimensional) flow solution is extended to several body lengths away from the airplane
- The pressure signature at a given distance below the airplane is used as input to a code that propagates the signature all the way to the ground
- An acoustics code then calculates the predicted loudness of the signature at ground level



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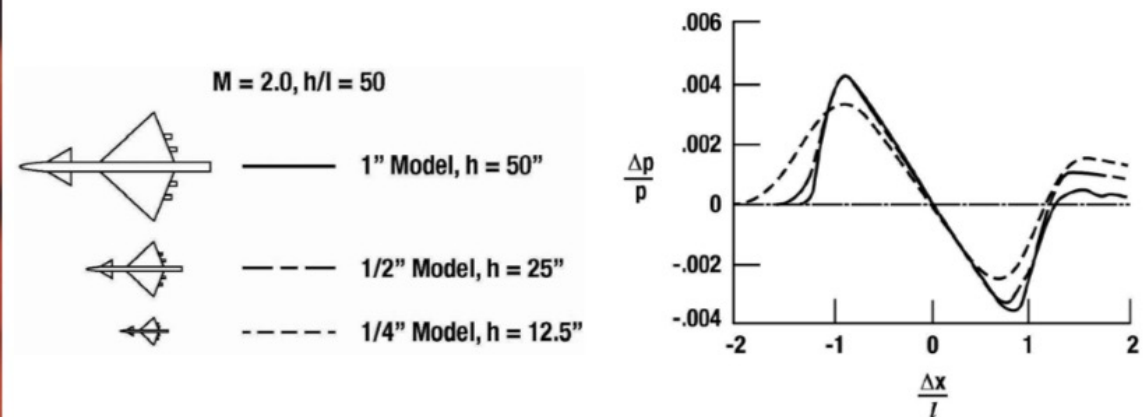
Mid-60's Langley Sonic Boom Tests

- Compared signatures for different model sizes
- Models made of XB-70, B-58, other supersonic concepts
- Tests conducted in Langley Unitary 4x4-ft Supersonic Wind Tunnels



(NASA photo, Courtesy of Harry Carlson)

Figure 9.4. Small sonic boom wind-tunnel models tested in the wind tunnel (ref. 9.1).



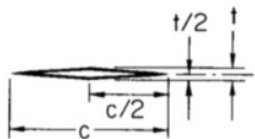
Maglieri et al, SONIC BOOM: Six Decades of Research, NASA/SP-2014-622, p. 396

Carlson & Morris, Wind Tunnel Sonic Boom Testing Techniques, Journal of Aircraft v. 4, no. 3, May-June 1967

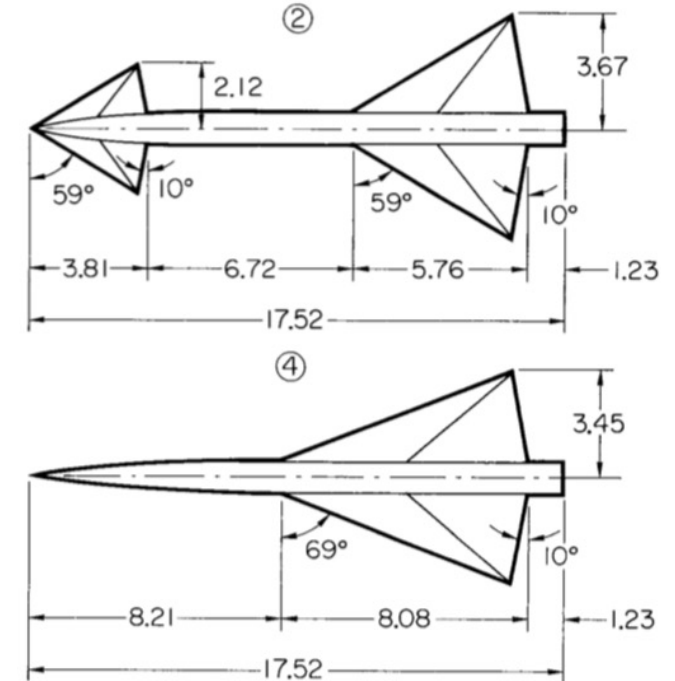
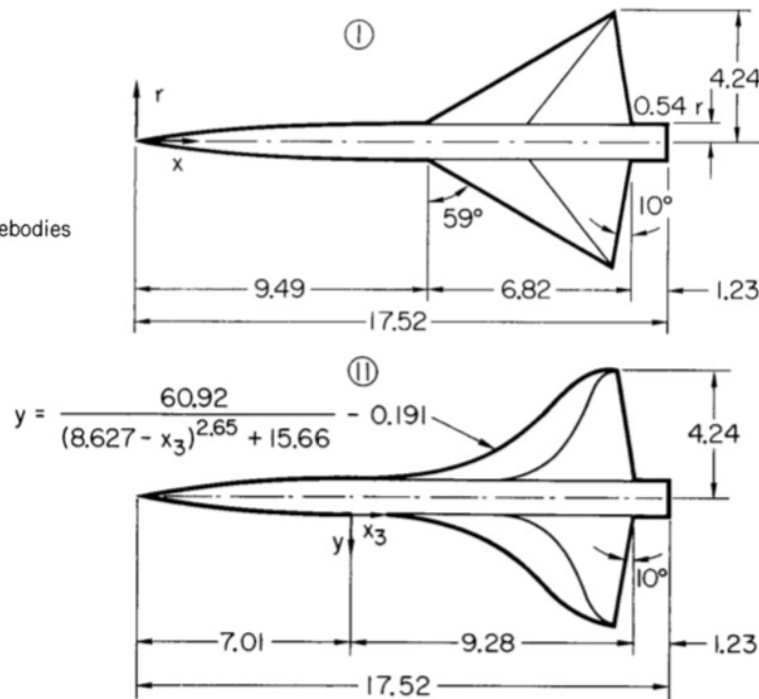
Early 70's Ames Sonic Boom Tests

- Studies of planform effects
- 12 models: delta wings, swept edges, and curved edges
- Mach 1.68, 2.0 (Ames 9x7) and Mach 2.7 (Ames 8x7)

All dimensions are in cm ;
 $r = 0.540 - 0.011(x - 7.01)^2$ for all forebodies



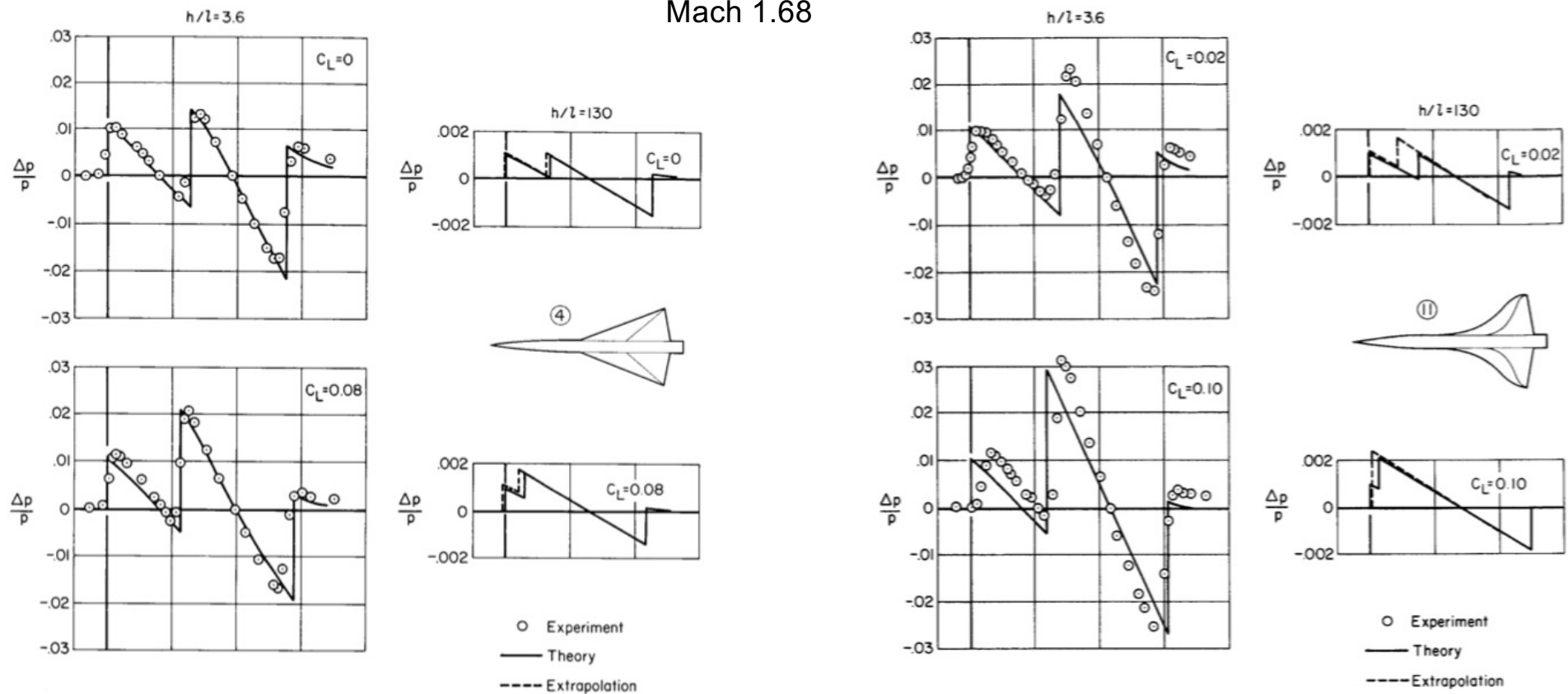
$t/c = 0.05$
 for all wing sections



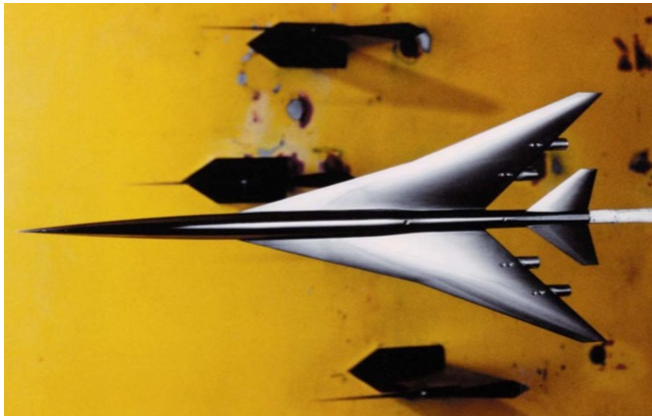
Early 70's Ames Sonic Boom Tests

Example signatures: comparison of theory and experiment for straight and curved delta wings

Mach 1.68



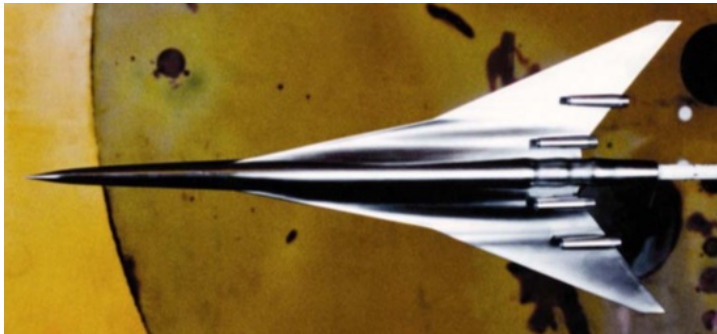
Early 90's Ames Sonic Boom Tests (9x7-Ft Wind Tunnel)



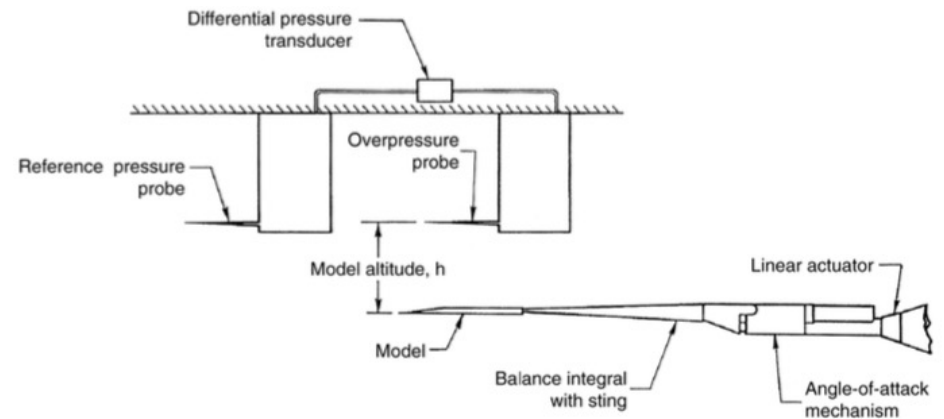
Low-boom wing-tail model



Low-boom wing-canard model



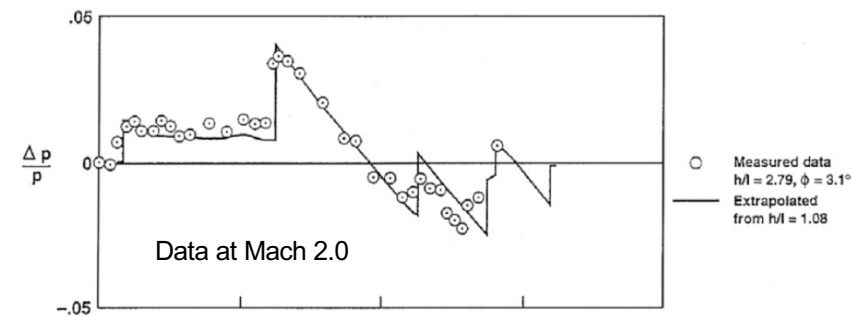
Boeing 1080-911 configuration



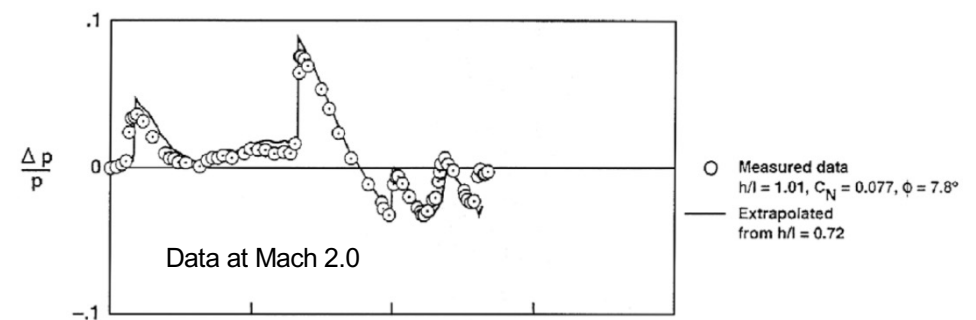
Early 90's Ames Sonic Boom Tests (9x7-Ft Wind Tunnel)



Langley Mach 2 model



Langley Mach 3 model



2008 Sonic Boom Test in Ames 9x7 — Probes and Rails

- Evaluated several pressure rails to acquire a line of data at one time instead of moving the model or probes in small increments over many minutes

Ames 2°
Conical Probe
on 10" Probe
Holder



1.25" Wall
Probe Rail



5.25" Wall
Probe Rail



Traversing
triple probe



18" Mast
Probe Rail

Lockheed and Boeing Concepts Tested in Wind Tunnels



- In 2009, NASA contracted Lockheed and Boeing to design future supersonic commercial transports that would have quiet sonic booms
- Small-scale wind tunnel models were made of these concepts and were tested in NASA Ames and Glenn supersonic wind tunnels



Image credit: The Boeing Company
https://www.nasa.gov/aero/centers_tackle_sonic_boom.html



Image credit: Lockheed Martin Corporation
<https://www.lockheedmartin.com/en-us/news/features/2016/webt-supersonic-flight-hush-sonic-boom.html>

Boeing Low-Boom 0.65%-Scale Model in Ames 9x7-Ft Supersonic Wind Tunnel



SONIC BOOM WIND TUNNEL TESTING 101

- This model is 15.75" long
- Pressure rail on side wall of tunnel has 420 tiny orifices along 66" of its thin edge for measuring pressure distribution below underside of model
- Pressure distribution shows us where shock and expansion waves are below model, such as on ground track under airplane flying overhead
- Computer codes are used to theoretically extrapolate these pressures to ground level, from which we calculate boom loudness



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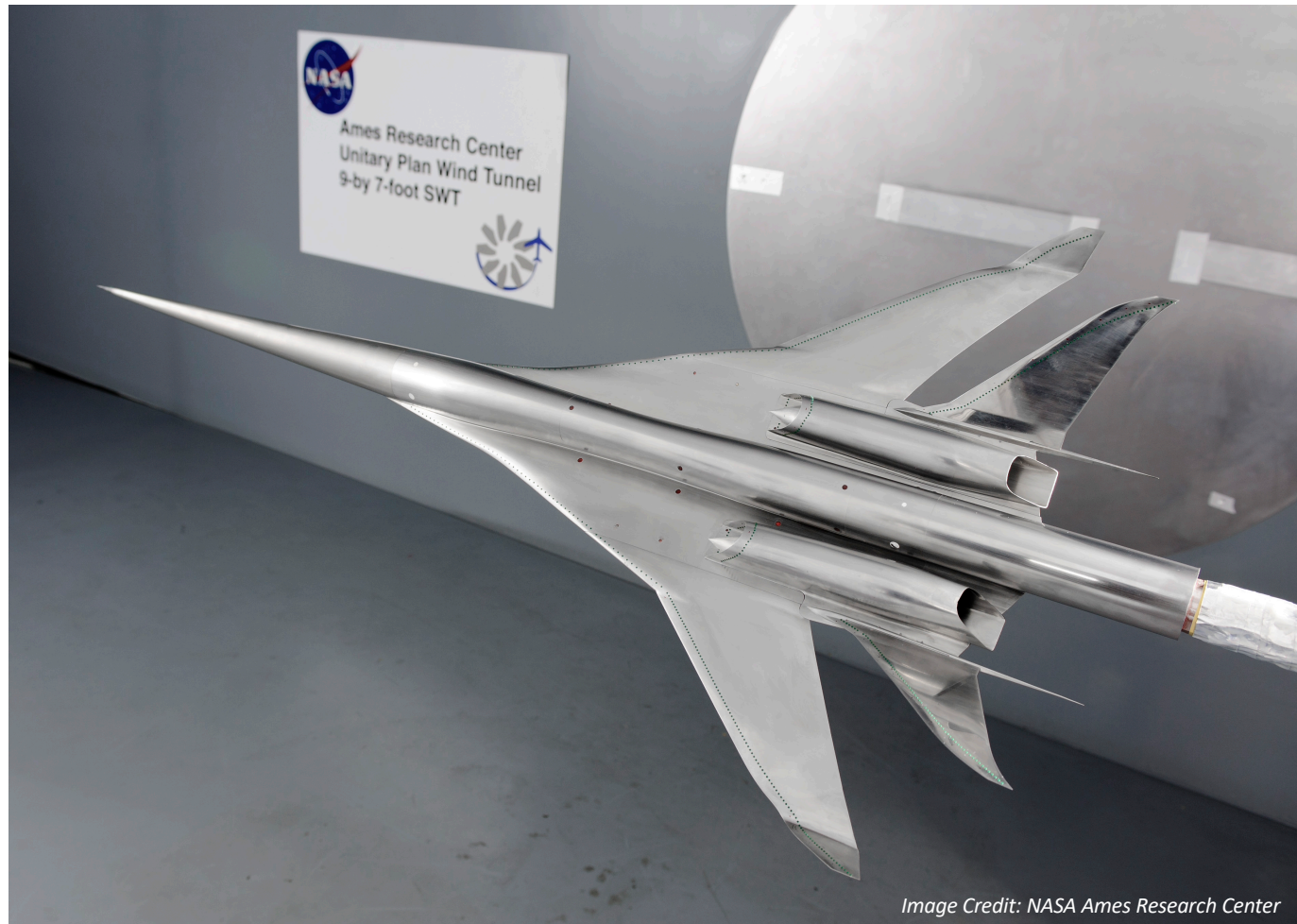


Image Credit: NASA Ames Research Center

Boeing Low-Boom 1.79%-Scale Model in Ames 9x7-Ft Supersonic Wind Tunnel



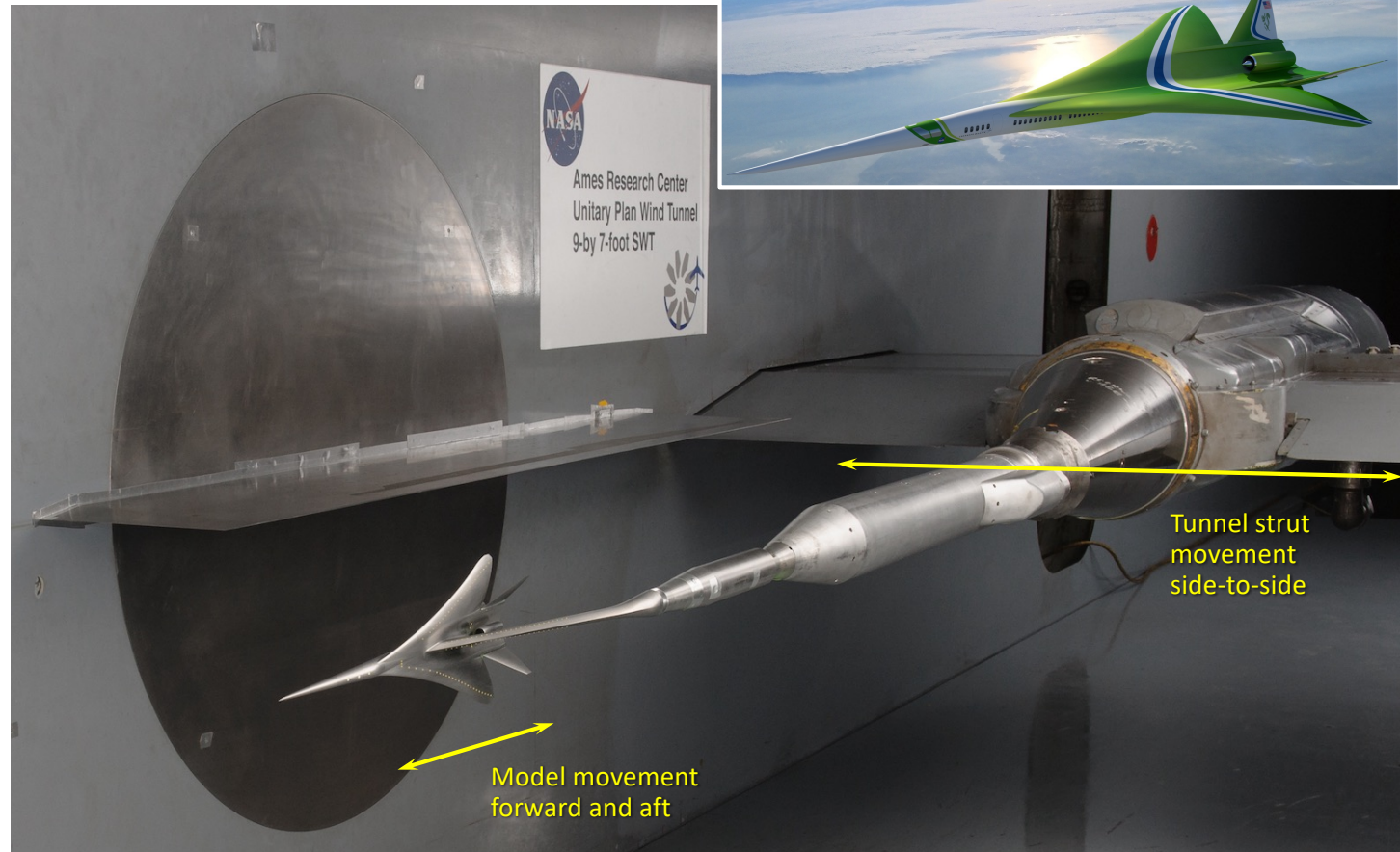
- Same airplane configuration as model on previous slide, but this model is 2.75 times larger
- Larger model was used primarily for aerodynamic measurements (lift, drag, etc)
- It is not very suitable for sonic boom measurements because it is too long (43") for the pressure rail (66"-long instrumented length)
- Combination of this model and the small model give us the aerodynamics and sonic boom pressure signature — both are critical for validating airplane design



Lockheed Low-Boom 0.8%-Scale Model in Ames 9x7-Ft Supersonic Wind Tunnel



- Support hardware in tunnel allows movement of model
 - fore and aft for measuring pressures along length of rail
 - side to side for varying distance from model to rail
- Hundreds of test conditions and model positions and angles are run in a test
- Typical sonic boom test takes about two weeks of running at two shifts per day
- This tunnel is power-hungry—cost of electricity (uses up to 175 MW) + personnel + maintenance costs are almost \$3/second!



Schlieren Image of Boeing 0.65%-Scale Model in Glenn 8x6-Ft Supersonic Wind Tunnel



- Schlieren is German for “streak”
- Bright, columnated light is shone across tunnel through side windows
- Shock and expansion waves show up as density gradients in the flow
- Test condition: Mach 1.8 (about 1200 mph)
- 56.3° shock wave angle from vertical = $\cos^{-1}(1/M)$

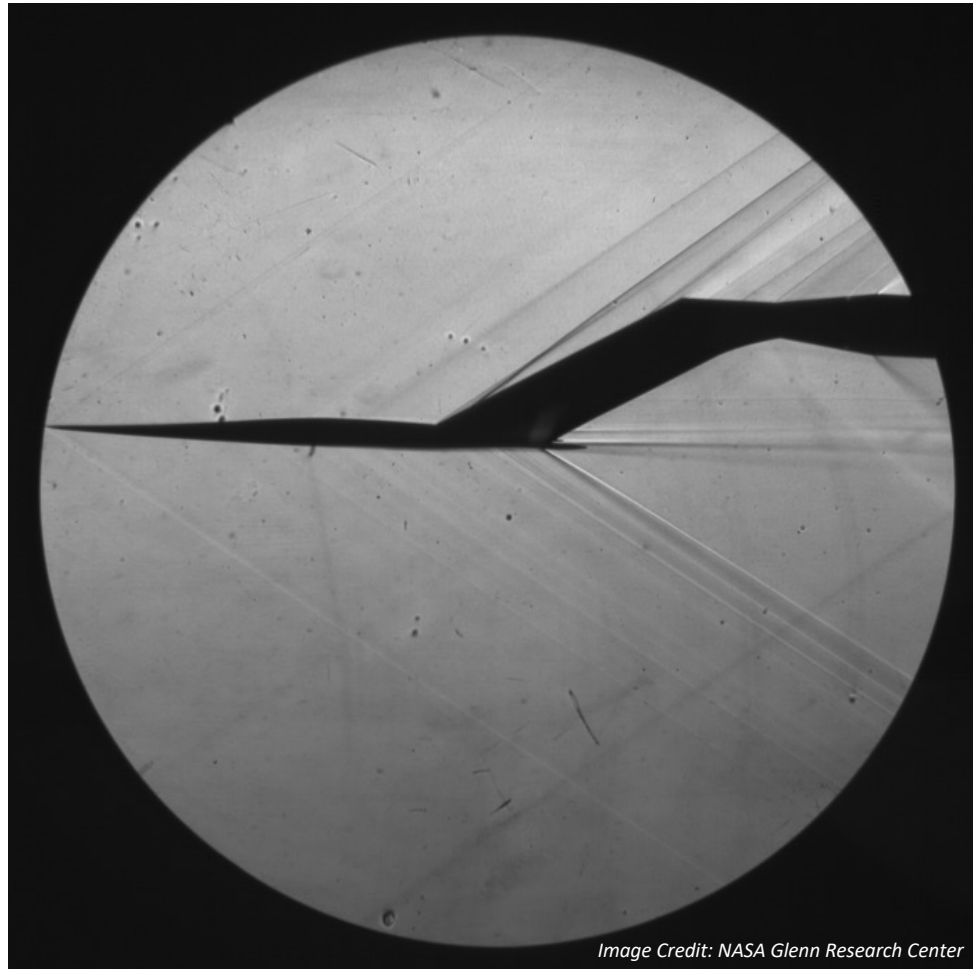


Image Credit: NASA Glenn Research Center

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AirBOS Image of T-38 in Flight

AirBOS: Air Background-Oriented Schlieren

- Target airplane makes supersonic pass below camera airplane (typically the NASA King Air)
- Multiple images taken
- Distortions in viewing background are caused by shock wave density gradients
- Aligning images and processing results gives clean view of flow field without background

*Image Credit: NASA Ames Research Center and NASA Armstrong Flight Research Center
<https://aviationweek.com/aviation-week-space-technology/2015-09-07>*

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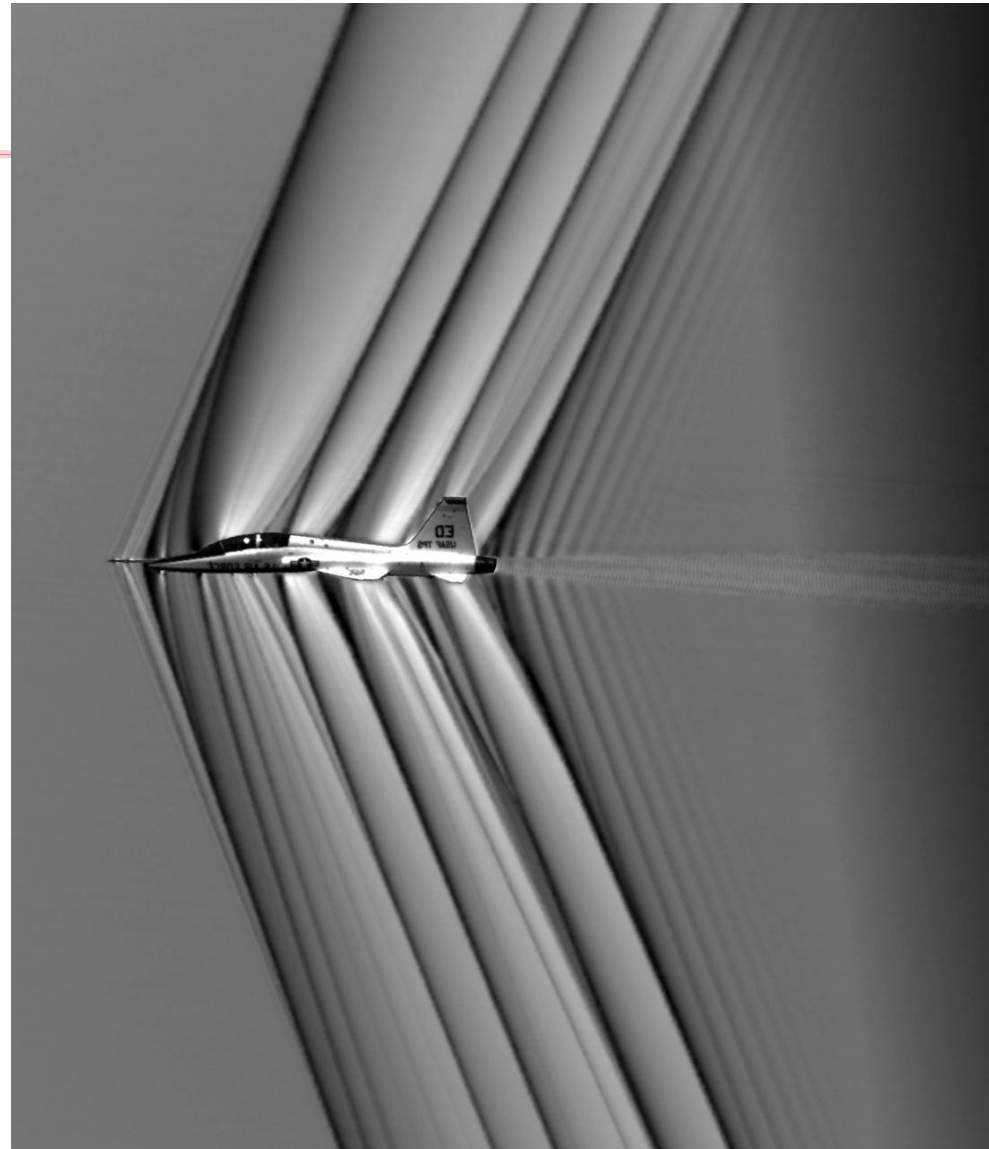


AirBOS Image of T-38 in Flight

- T-38 supersonic jet flying at Mach ~ 1.08
- Series of high-speed photographic images were processed to reveal the structure of shock and expansion waves above and below the aircraft
- Lots of flow detail visible close to the aircraft, but shocks merge as they get further away

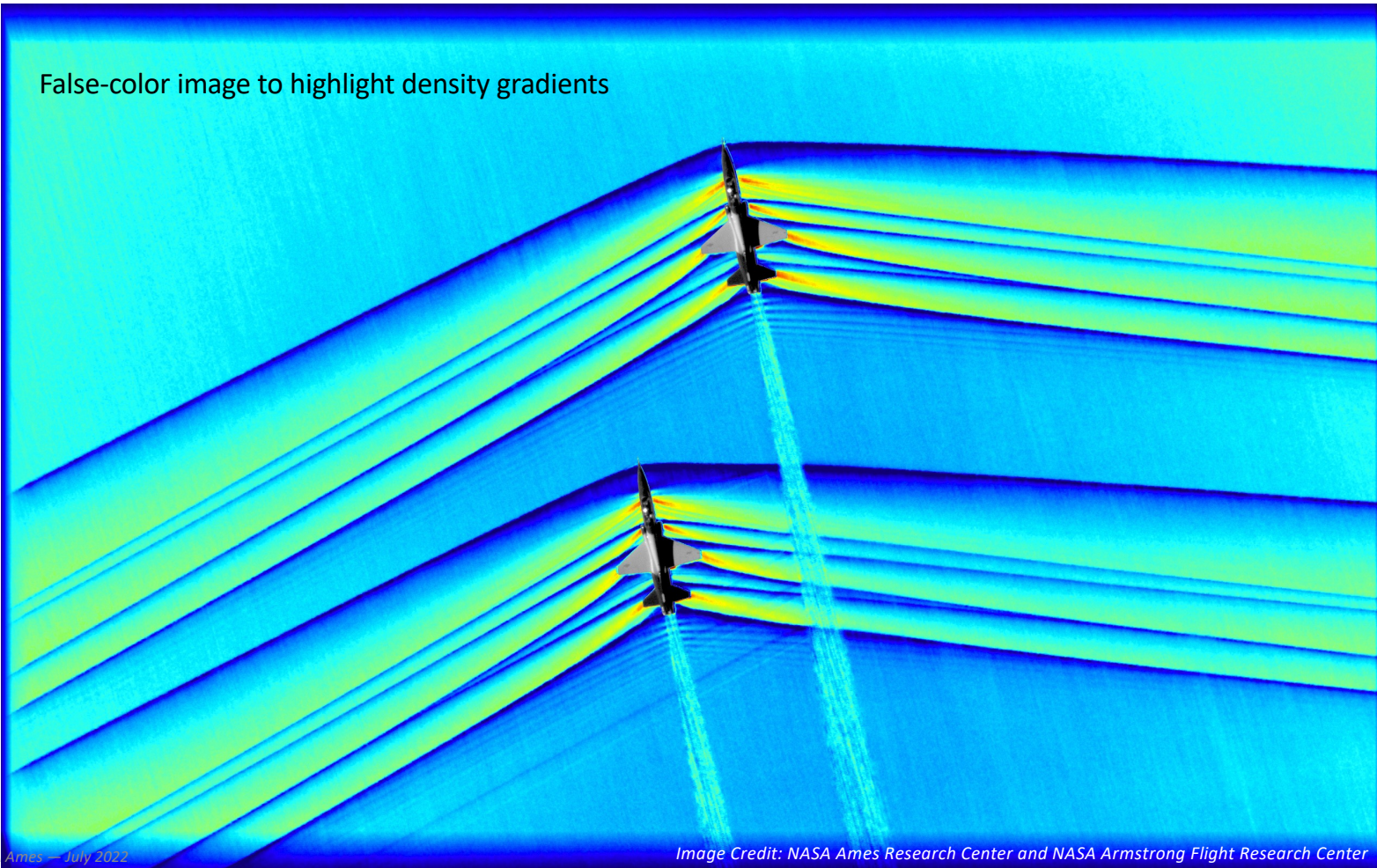
*Image Credit: NASA Ames Research Center and NASA Armstrong Flight Research Center
<https://www.nasa.gov/centers/armstrong/features/supersonic-shockwave-interaction.html>*

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AirBOS Image of Two T-38s in Formation

False-color image to highlight density gradients



BOSCO Image of T-38 in Flight

BOSCO:
Background-Oriented Schlieren
using Celestial Objects

- Target airplane makes supersonic pass between sun and observer
- Observer on ground takes multiple images

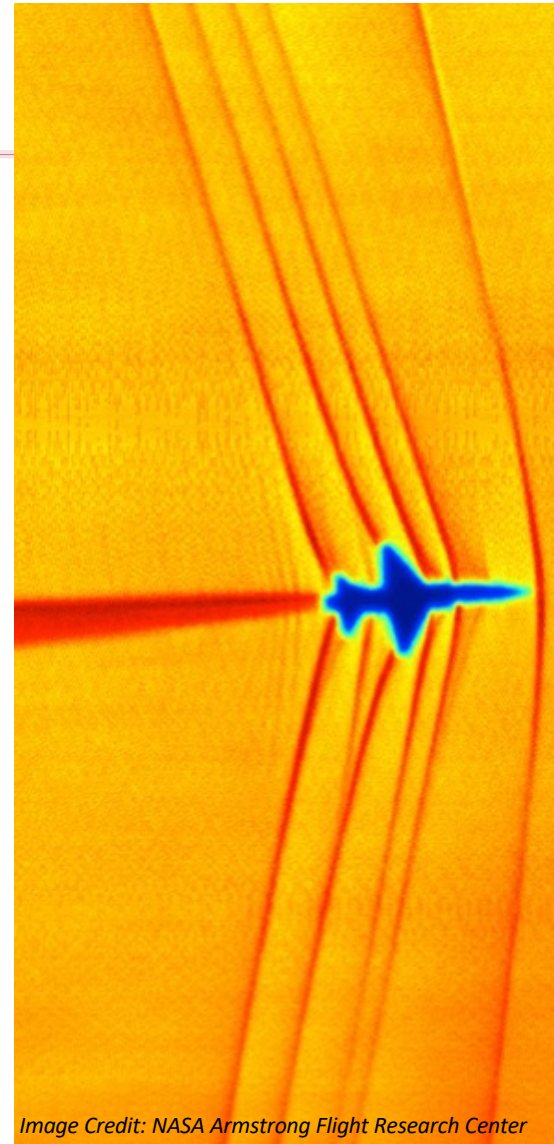


Image Credit: NASA Armstrong Flight Research Center

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Quesst Mission

*...to demonstrate quiet
sonic boom technology*

NASA X-59



Quesst Mission Goal and Schedule

- *Goal is FAA (Federal Aviation Administration) and ICAO (International Civil Aviation Organization) rule change to allow supersonic flight over land for aircraft that have quiet sonic boom*
- *Opens door for development of a new generation of environmentally-friendly supersonic civil transport aircraft*

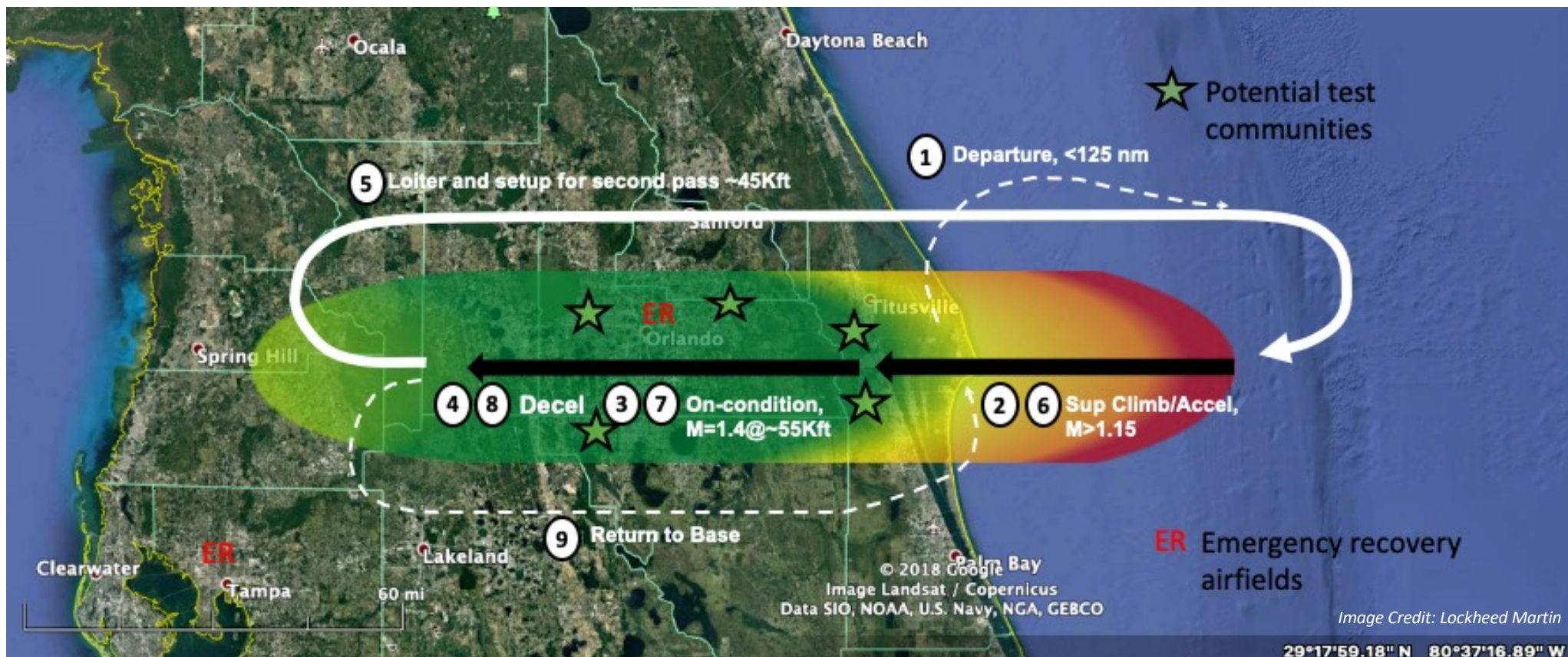


- *June 2017: Preliminary Design Review*
- *April 2018: Contract award to Lockheed Martin to build aircraft*
- *2022–2023: First flight, envelope expansion, boom validation testing*
- *2024 & later: Flight tests over populated areas to get community responses*



Mission Profile for X-59 Flights

Concept of Operations: Representative Community Response Deployment



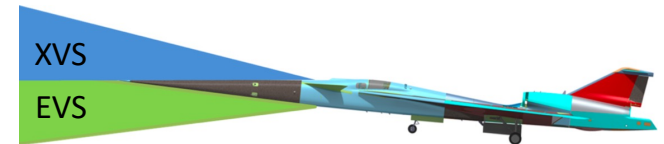
X-59 eXternal Vision System



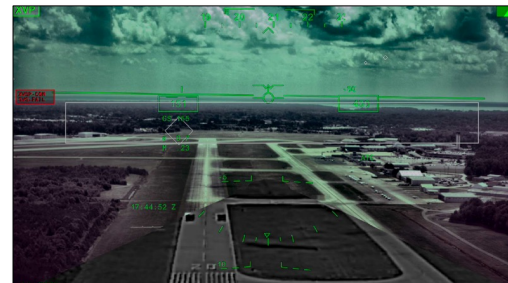
Concept View of X-59 Cockpit

Camera Viewing Angles

eXternal Vision System
Enhanced Vision System



Cameras on Flight Test Aircraft



XVS Image During Flight Test



XVS Station in Flight Test Aircraft

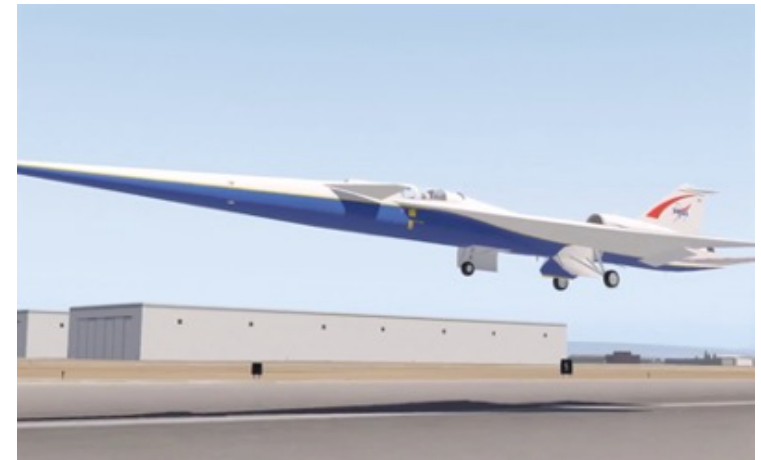
Flight Simulator Development

- Aircraft and cockpit simulations validate aircraft designs, systems, and performance – also used for pilot training and flight planning



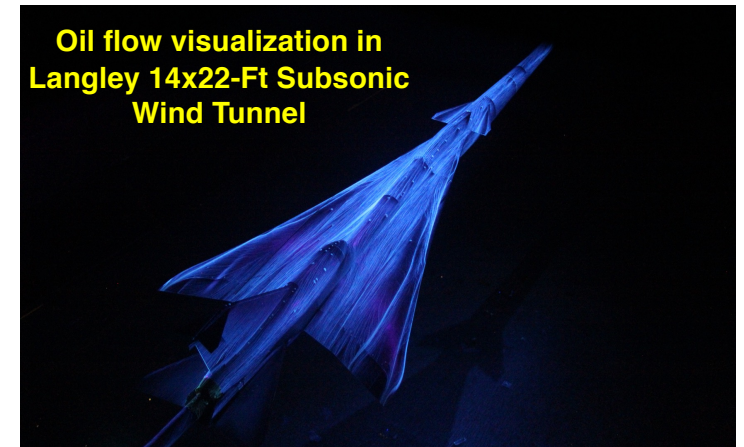
X-59 Flight Simulator Models Available for Download

- Undergraduate interns at NASA Ames, Armstrong, and Langley spent the summer of 2019 competing to develop a laptop flight simulator of the X-59
- Simulations were made in X-Plane software
- Students were given airplane geometry, but had to build up the aerodynamics, propulsion, stability and control on their own
- Each team made a promotional video of their configuration
- Simulation models available for download



X-59 Wind Tunnel Validations

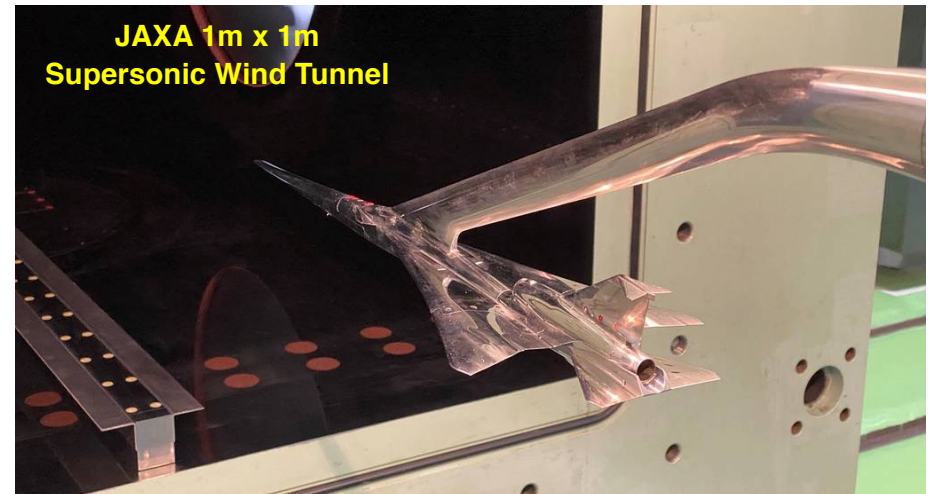
Low- and high-speed aerodynamic and Propulsion/Airframe Interaction (PAI) wind-tunnel tests validate predictions and ensure readiness of the design



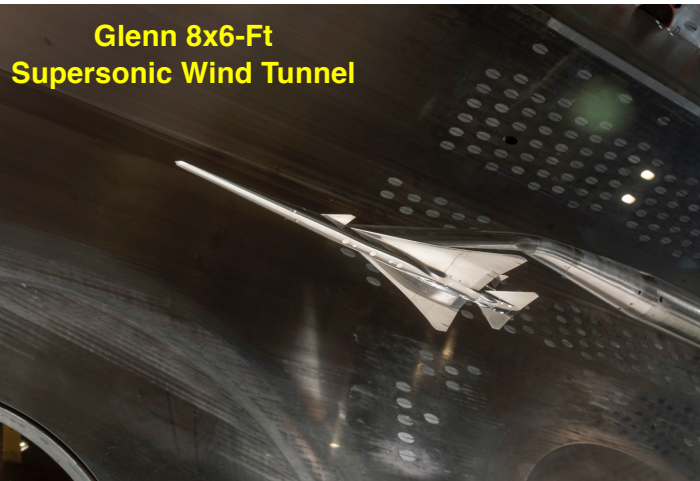
X-59 Wind Tunnel Validations



Sonic boom
wind-tunnel tests
conducted on
1.62%-Scale X-59
model



**JAXA 1m x 1m
Supersonic Wind Tunnel**



**Glenn 8x6-Ft
Supersonic Wind Tunnel**

Image Credits:
Quentin Schwinn,
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NASA Video on X-59, interviews with Nils Larson, Cathy Bahm, Larry Cliatt, others



*Video removed to
reduce file size,
video available from
author upon request*

Don Durston, NASA Ames — July 2022

Any Questions?



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